OPTICALLY AMPLIFIED RECEIVER

Field of the Invention

This invention relates to communication receivers, and more particularly, this invention relates to communication receivers that convert optical communication signals.

Background of the Invention

The bandwidth of single channel (or wavelength) fiber optic telecommunication links is mainly limited by the high-speed electronics required at the transmitter and receiver. Wavelength division multiplexing of optical communication signals is a technique used for increasing the bandwidth of a fiber optic telecommunications link, without increasing the speed of the electronics. At the communications receiver, the optical channels that receive optical communication signals must be separated, or demultiplexed, and sent to their individual receivers, which vary in their rate of data receipt. One example is 2.488 Gb/s receivers.

The demultiplexing process is not ideal and optical losses are incurred, thus reducing the overall receiver sensitivity. A reduction in sensitivity also translates into shorter transmission lengths for the overall telecommunications link. When components are optimized on an individual basis, the benefits of any smaller size and lower power operation are not achieved with these type of receiver architectures. One current

method of achieving high sensitivities in a wavelength division multiplexed receiver is the use of a wavelength demultiplexer with avalanche photodiodes (APD). These electronically amplified optical receivers have been designed as separate units in a rack-mounted configuration. Typically, each card unit within a rack-mounted configuration represents an individual component, forming a very large, but undesirable unit, especially in low power applications, as in advanced aircraft designs or other design specifications where low power and small footprint are desired.

Because these types of optical receivers are rack-mounted units and use avalanche photodiodes, the receiver sensitivity power penalty is incurred approximately equal to the optical insertion loss of the optical demultiplexer. Typically, telecommunications receivers using optical pre-amplification are not optimized for both high sensitivity and low power, and are not contained within a single assembly. Also, in some optical communication receivers, a laser driver may be necessary. To deliver the current necessary to power a laser diode, an electric circuit is used and supplies power to the laser driver, but also dissipates power of its own. This power, which is dissipated in the control circuit, is essentially wasted power, because it is not converted into photons.

Some current design injection laser diode drivers use a linear pass transistor to deliver a regulated current to the injection laser diode. This method results in a constant voltage across the device and constant current through the device, resulting in a large amount of dissipated power. For example, nearly 90% of all power dissipated by the injection laser

diode driver occurs in the pass transistor, in some prior art designs. Thus, there is a necessary requirement and solution desired to deliver a clean current source to the injection laser diode.

Summary of the Invention

It is therefore an object of the present invention to provide an optimized and fully integrated, high sensitivity, power efficient, optically amplified receiver that is optimized as a system and incorporated into a single assembly.

It is still another object of the present invention to provide an optically amplified receiver that allows increased transmission distances over the currently available technology, reduces the volume of valuable equipment-rack space, and provides more effective thermal management.

The present invention is advantageous and provides an integrated optically amplified receiver that reduces power consumption and is beneficial for the large channel count and high data rate systems of modern communication systems. Noise performance of the receiver electronics can be traded with lower power operation. The receiver includes a high level of integration and allows incorporation of common substrate thermal management. By designing the optically amplified receiver components to be optimized as a system and incorporating them into a single assembly, it is possible to increase transmission distances over currently available technology, reduce the volume of valuable equipment-rack space, and provide more effective thermal management. The use of erbium-doped fiber amplifier technology also allows PIN detectors to be used in place of the avalanche photodiode as the optical-to-electrical converter, thus

increasing the overall reliability of the receiver to reduce power consumption.

The high receiver sensitivity and component reliability that is achievable with the optical amplifiers and PIN detectors are integrated with customized low power pump laser drivers and receiver technologies to allow simplification and efficiency.

In accordance with the present invention, the optically amplified receiver includes an optical preamplifier for receiving an optical communications signal over an optical communications line, which in one aspect of the invention, is a single optical communications line for receiving a wavelength division multiplexed signal. A bandpass filter is operatively connected to the optical preamplifier and receives the optical communication signal, selects a single wavelength division multiplexed signal and filters out noise produced by the optical preamplifier. The optical preamplifier, in one aspect of the invention, is a low noise, gain flattened, erbium doped optical preamplifier.

A laser driver is interfaced with a laser used to pump the optical preamplifier and includes an injection laser diode and a current source control loop circuit connected to the injection laser diode that establishes a fixed current through the injection laser diode. A voltage switcher circuit is connected to the injection laser diode and current source control loop circuit. This voltage switcher circuit is adapted to receive a fixed supply voltage and convert inductively the supply voltage down to a forward voltage to bias the injection laser diode and produce an optical output into the preamplifier having minimized power losses.

In yet another aspect of the present invention, a demultiplexer filter is operatively

connected to the low noise, gain flattened, erbium doped optical preamplifier for demultiplexing the wave division multiplexed optical signal into a demultiplexed optical signal. A plurality of receiver channels receive the demultiplexed optical signals. An optical-to-electrical conversion circuit is positioned within each receiver channel and converts the optical signals into electrical communication signals.

One of either a housing or circuit card contains the optical preamplifier, laser driver, demultiplexer filter and optical-to-electrical conversion circuit as an integral receiver assembly. The bandpass filter is operatively connected to the optical preamplifier for receiving the optical communication signal and filtering out noise produced by the optical preamplifier. This bandpass filter can comprise a tunable bandpass filter.

The optical-to-electrical conversion circuit can include a PIN detector and an amplifier circuit connected to the PIN detector for amplifying the electrical communication signals. In yet another aspect of the present invention, the amplifier circuit can comprise an integration circuit, decision circuit and clock recovery circuit. In yet another aspect of the present invention, the amplifier circuit can comprise a demodulator for analog transmission signals.

Brief Description of the Drawings

Other objects, features and advantages of the present invention will become apparent from the detailed description of the invention which follows, when considered in light of the accompanying drawings in which:

FIG. 1 is a high level diagram showing an example of a low-noise, wavelength division multiplexed

receiver of the present invention, connected to a star coupler and in-line, erbium doped, fiber amplifier repeater.

FIG. 2 is a block diagram of one example of an optically amplified receiver of the present invention.

FIG. 3 is a block diagram showing an example of the laser driver/power converter of the present invention, which is used as part of the optically amplified receiver.

FIG. 4 is a block diagram showing an example of a power splitter/optical bandpass tunable filter, demultiplexer that can be used with the present invention.

FIG. 5 is a schematic diagram of a power splitter that can be used with the present invention.

FIG. 6 is a graph showing the bit error rate versus input optical power in dBm, as an example of the present invention.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

The present invention provides a highly engineered, optimized, and fully integrated, high sensitivity wavelength division demultiplexed optically

amplified receiver that is designed to be used preferably with a single input fiber, having multiple wavelengths of communication signals. Also, the receiver allows significant power savings by using a laser driver that has reduced power over many current state-of-the-art continuous wave laser drivers.

This power savings is accomplished by using a standard current source control loop configuration that is set to the desired current through an injection laser diode. The current source has been optimized by using state-of-the-art components to minimize the amount of wasted power, i.e., power not delivered to the injection laser diode. The laser driver also has a current source that is a high efficiency variable voltage switcher having an output voltage that is varied, such that there is minimal voltage drop across each of the components in the current source leg, thus wasting no excess power. These power savings can be diverted to other circuits in the system, and can allow a battery powered device to last longer with increased financial and energy savings.

In one aspect of the present invention, a switching current source is used for driving the injection laser diode in the optic preamplifier such that inefficient linear drivers are replaced. The current injection laser diodes used in many prior art devices are inefficient and operate on the order of 300 mW, to deliver the optic power to an erbium-doped gain element.

Some injection laser diode drivers use a linear pass transistor to deliver the regulated current to the injection laser diode. This results in a constant voltage across and constant current through the device, resulting in a large amount of dissipated

power, and in some instances, nearly 90% occurring at the pass transistor.

The present invention allows a clean current to be delivered to the injection laser diode from a switching pass transistor, which is alternatively operated in the "full on," then the "full off" mode. When in the "full on" mode, there is no voltage across the transistor. When in the "full off" mode, no current flows through the transistor. As a result, the switching pass transistor dissipates a reduced amount of power. By allocating the switcher operating parameters based on characteristics of the injection laser diode and the erbium gain element, the switcher noise is maintained in a manner consistent with the high performance of the optical amplifier. Expected efficiency improvements are reduction of the pass transistor power to approximately 15% of total driver power, and total net efficiencies, including the injection laser diode, in the range of up to about 30%. This allows additional fibers to be placed in cables.

The present invention also provides a wavelength division multiplexed and low power optically amplified receiver that is fully integrated and optimized with high sensitivity. It incorporates low power engineering and has a customized high efficiency pump laser driver as described before, and thermo-electric coolerless operation of the pump laser. It allows silicon based chip technology in the receiver. In one aspect of the invention, as a non-limiting example only, it is optimized and integrated for achieving high sensitivity in the form of eight different channels at 2.488 Gb/s channels based at 100 GHz (0.8 nM).

The receiver, in one aspect of the invention, uses a single input fiber with multiple wavelengths as

described. It has a low noise, gain flattened erbium doped fiber amplifier that acts as a preamplifier, followed by a low loss demultiplexer with minimal variation in channel-to-channel output power. A receiver array then follows and includes in each receiver a PIN detector and high speed electronics.

As noted before, the bandwidth of a single channel or wavelength fiber optic telecommunication link is limited by the high-speed electronics required at the transmitter and receiver. Although various channel data rates are known, the present invention will be described relative to data rates of about 2.5 Gb/s. Naturally, the design can be used with increased data rates. Some state-of-the-art optical receivers for single channel fiber optic telecommunication links operate at 2.488 Gb/s, and are limited to operating at a bit/error ratio of $1x10^{-11}$ at incident optical powers of -34 dBm. Wavelength division multiplexing (WDM) increases the bandwidth of a fiber optic telecommunications link without requiring an increase in the speed of electronics. This technique multiplexes multiple channels and wavelengths, each modulated at, as a non-limiting example, 2.488 Gb/s, onto a single fiber. This aggregate bit rate of the fiber now becomes N x 2.488 Gb/s where N=2, 3, 4, ... At the receiver, the optical channels are separated and demultiplexed and sent to their individual 2.488 Gb/s receivers.

The demultiplexing process is not ideal and optical losses are incurred, thus reducing the overall receiver sensitivity. This translates to shorter transmission lengths. By incorporating the optic preamplifier based on the erbium doped fiber technology of the present invention, the demultiplexer losses are overcome and can increase the signal level well above

the receiver noise floor and increase the receiver sensitivity. The erbium doped fiber amplifier technology allows the use of PIN detectors in place of avalanche photo diodes as an optical-to-electrical converter. By optimizing each of the individual components and incorporating them into a single unit, the invention not only increases transmission distances over currently available technology, but also reduces the volume of equipment-rack space.

Referring now to the drawing figures, a more detailed description of the invention follows.

FIG. 1 illustrates a wavelength division multiplexed optical network **10** where various signals λ1, λ2, λ3, λ4 come through a plurality of optical fiber channels **12** as fiber optic lines into a trunk optical fiber **14** and into an in-line erbium doped fiber amplifier repeater **16** to a star coupler **18**. Different signal branches **20** (ON-1, . . . ON-N) extend from the star coupler **18**, where one branch (or channel) is illustrated as having optical receiver **28**, and a low noise erbium doped fiber amplifier **22** and an optical bandpass tunable filter **24** followed by a photo receiver **26**, such as working at 2.5 Gb/s.

FIG. 2 illustrates at **30** an optically amplified receiver of the present invention contained in housing, or in another aspect of the invention, on a printed circuit card assembly **31**. In one aspect, components are mounted on a single printed circuit card assembly, which can be mounted in one housing, and forming an integral receiver assembly. Although the description will proceed relative to a description with non-limiting data rates of 2.5 Gb/s, it should be understood by all those skilled in the art that the invention can be applied to different data rates.

As shown in FIG. 2, the signal P_S enters the erbium doped fiber preamplifier **32**, acting as an optical preamplifier. The relative operating parameters for the illustrated preamplifier **32**, tunable bandpass filter circuit **34** and optical-to-electrical conversion circuit **36**, are illustrated relative to the appropriate blocks. The bandpass filter receives the signal from the optical preamplifier, selects a single channel, and filters out noise produced by the optical preamplifier in a manner known to those skilled in the art.

In one aspect of the invention, the tunable bandpass filter circuit **34** of the present invention includes a power splitter **40** and optical bandpass tunable filters **42**, as shown in FIGS. 4 and 5, where the power splitter **40** is shown as cascaded 3-dB couplers **44**. Although this illustrates only one type of power splitter/optical bandpass tunable filter and demultiplexer that can be used with the present invention, it should be understood that different types of circuits can be used with the present invention.

In one aspect of the present invention, the optical-to-electrical conversion circuit **36** includes a PIN detector (diode) **50**, followed by a low-noise electrical amplifier **52**. An electronic limiting amplifier **54** works in conjunction with decision circuit **56** and allows data recovery and reshapes electrical communication signals, while a clock recovery circuit **58** allows recovery of clock signals and retiming of electrical communication signals.

FIG. 3 illustrates the low power laser driver circuit **60** of the present invention, which is used for driving the optical preamplifier and receiver assembly. The five volt supply voltage input is standard with

many electronic circuits. The laser driver circuit **60** includes an injection laser diode **62** that is, in one aspect of the present invention, a quantum efficiency injection laser diode (HQEILD). A current source control loop circuit **64** is connected to the injection laser diode **62** and establishes a fixed current through the injection laser diode. This current source control loop circuit **64** has a voltage switcher circuit chip **66** connected to the injection laser diode, within the current source control loop circuit, and is adapted to receive the fixed supply voltage of five volts and convert inductively the supply voltage down to a forward voltage, to bias the laser injection diode and produce an optical output having minimized power losses.

This voltage switcher circuit chip **66** is monolithically formed as a single circuit chip, and is used as a high efficiency voltage converter as shown in FIG. 3.

The current source control loop circuit **64** includes the high efficiency current source **70**, acting as a low noise current source and the current control circuit **72**. These circuits are all contained within one housing, and in one aspect, on a printed circuit card assembly **74** that includes the receiver components, including the preamplifier, tunable bandpass filter circuit and optical-to-electrical conversion circuit.

The schematic circuit diagram shows various power and voltage, as well as current parameters. In this non-limiting example, at 260 milliwatts and at five volts DC, there is a 35 decibel optical gain, with one channel as a design goal. There could be a 266 milliwatt DC for eight channels, and 220 milliwatts DC achieved. The Bragg grating **73** is operatively

connected to the injection laser diode **62**, and is operative by principles known to those skilled in the art. The Bragg grating **73** is configured for receiving the optical output and stabilizing the optical wavelength.

FIG. 5 illustrates a graph showing the log of base 10 for the bit error rate (BER) versus the input optical power (in dBm). The square dots represent a PIN only receiver, without optical amplifier, while the triangular dots represent the optically amplified PIN receiver of the present invention. There is illustrated on the graph an 18 decibel improvement in system sensitivity using the optically preamplified receiver of the present invention.

This application is related to copending patent applications entitled, **"LOW POWER LASER DRIVER"** which is filed on the same date and by the same assignee and inventors, the disclosure which is hereby incorporated by reference.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that the modifications and embodiments are intended to be included within the scope of the dependent claims.